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System parameter identification theory and uncertainty analysis methods for multi-zone building heat transfer and infiltration

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A B S T R A C T

Methods for on-site measurement of building thermal performance system parameters such as coefficient of heat loss, solar heat gain, effective thermal capacity, infiltration rate, and effective mixing volume are very important, yet a nontrivial task. Although these are steady-state parameters, on-site measurements are exposed to changing meteorological conditions and are affected by the thermal capacity of the building. In addition, these parameters should generally be estimated by using a multi-zone model such as inter-zone flow rates. In this regard, a state space equation model, referred to as a "thermal network model," has been devised to generalize such multi-zone heat transfer system and tracer gas diffusion system measurements. This model is composed of three parameter types, and we have developed a system parameter identification theory and uncertainty analysis method using least squares, as well as actual measurement systems. In the present paper, we improve the least-squares regression equation, the uncertainty analysis method, and the reliability evaluation method. We investigate appropriate excitation waveforms and frequencies for heating and tracer gas release, as well as a low-pass filter for pre-processing measurement data. We verify these theories and methods using computer-simulated measurement.

1. Introduction

Parameters related to the energy efficiency of heating and cooling, as well as to the thermal comfort of the building environment, include the coefficient of external wall heat transmission, solar heat gain, and effective thermal capacity. In addition, parameters such as infiltration rate and effective mixing volume are related to healthy indoor air quality. In this regard, it is necessary to develop methods for on-site measurements of these system parameters, because buildings might not have been built in accordance with plans and from specified materials, components might have deformed, or material performance may have deteriorated.

In contrast to measurements performed on test buildings constructed in laboratories in an artificial climate, it is difficult to establish these system parameters through on-site measurements on actual buildings, because outdoor fluctuations in temperature and solar radiation and the influence of the tested building's thermal capacity make conditions unstable. Furthermore, it may be necessary to apply a multi-zone model to estimate inter-zone flow rates and heat transmission coefficients.

In Japan, research into on-site measurement methods for assessing building performance began in the late 1970s with Matsuo et al. [1], who devised a method called Matsuo's digital filtering. Emura et al. improved upon Matsuo's method by using condensed orthogonal meteorological effects [2], and further developed an alternative estimation method for states and parameters [3]. Akashi et al. performed research on least-squares-based system identification methods for the static and dynamic thermal characteristics of office buildings, utilizing a transfer function model [4]. Hattori et al. [5] continue to research Matsuo's method. A recent version of Matsuo's method estimates the heat loss coefficient of a single-zone model by using step excitation from an electric heater. In the estimation process, time series response factors are calculated by the least-squares method. Most models are single-zone and require assumptions of invariability and linearity. These methods are insufficient for discerning simultaneous system identification of both thermal and infiltration systems. Excitations for this system identification are mainly researched using square wave or step functions with high-frequency sinusoidal components as the Fourier series expansion. Furthermore, these methods have unsolved problems related to estimating the parameters of solar

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heat gain and effective thermal capacity, as well as with evaluating the statistical uncertainty of these estimated parameters.

The state of the art is similar in other countries, where copious research has been performed mainly on single-zone models using various estimation methods, such as the recursive least-squares method developed by Zaheer-uddin [6], the iterative descent technique by Dewson et al. [7] (which involves an evaluation function of the root mean square of the predicted and the measured temperature), the autoregressive moving average method by Norlen [8], and the multi-variable time series least-squares method by Crawford et al. [9]. Baudier et al. [10] adopted a state space equation model and applied Marquardt's algorithm [11] to obtain parameters. Wang et al. [12] studied the application of genetic algorithms [13] to a simple thermal network. Another example is the two-node model developed by Jimenez et al. [14,15], which utilizes the MATLAB software package.

Okuyama [16] gives another possibility, a method with fewer measurement points than nodes in the system identification model. That method, however, requires measurement results for multiplex frequency sinusoidal excitation and accurate higher-order time derivatives, and furthermore has problems related to theoretical generalization.

Because of the complexity of heat transfer in buildings, simulation of changes in room temperature are assumed to require complex models consisting of many nodes, including the building structure, with varying solar heat gain coefficients. We note, however, that the parameters to be estimated are for simplified steady-state models, meaning that time-averaged parameters are sufficient for certain terms.

In contrast to heat transfer systems, system identification models for a tracer gas diffusion system used in multi-zone infiltration measurements can trace concentration changes accurately, even under a single-node model for each zone, by using mixing fans in each zone. System identification then becomes relatively easier than in the case of a thermal system. Extensive research on measurement methods for multi-zone airflow rates has been carried out; for example, 47 papers were cited by Miller et al. in the Introduction section of their paper [17]. Among these, Sherman, Prior, and O'Neill are frequently cited. Papers written by Japanese researchers, including Enai, Honma, and Okuyama, have also been introduced.

Such multi-zone heat transfer and infiltration systems, characterized by heat and tracer gas diffusion systems, respectively, can be represented by a general mathematical model (a thermal network model), even though the diffusion variables are different. It is well known that the various dynamic systems are described by the state space equation model in modern control theory. Jiang [18] and Hong [19] researched the formulation of and analytical solution for an application to building air-conditioning. However, the analytical solution can be improved by using the spectral resolution of a projection on eigenspaces [20], and the universally applicable modeling concept [21] devised by Okuyama.

Okuyama [22] derived two types of least-squares methods for batch identification and recursive identification of the thermal network state space equation model, the latter using the matrix inversion lemma introduced by Woodbury [23]. That study also developed the system identification program SPID. There, the recursive least-squares methods seemed to have the ability to follow parameter time variations, but performance did not live up to expectations. It was also realized that estimation accuracy was not higher than that for batch identification. A moving batch identification term that shifts the several-hour system identification term T by Δt was therefore investigated, and the method tested on actual buildings. Changes in infiltration rate in relation to the changes in indoor/outdoor temperature differences have been appropriately estimated and verified [24].

In recent years, Okuyama et al. developed a statistical data analysis method for steady-state multi-zone infiltration measurements using multiple perfluorocarbon tracers [25]. They introduced a discrepancy ratio β, which evaluates prerequisite validity for measurements and data analysis, and is also useful in heat transfer systems.

Our latest study [26], despite concerning a single-zone model with tracer gas pseudo-non-uniformity, revealed that low-frequency sinusoidal excitation enables satisfactory results, even in a rough system identification model of fewer nodes. We also found that a low-pass filter using moving term averages is necessary for pre-processing measurement data. We solved the problem of determining the optimum concentration decay term or, more generally, the optimum excitation stopping term. We furthermore found an appropriate calculation method for the uncertainty propagation equation, and the usefulness of both the coefficient of determination (*COD*) and the discrepancy ratio β for reliability evaluation.

The present paper improves the earlier theory [22], and confirms the aforementioned findings for the multi-zone system through use of a single-zone model [26]. Appropriate verification is impossible in case studies of actual buildings because the true system parameters are unknown. The first step in this study, therefore, is computer-simulated measurements, for which true or comparable reference values are known. When measuring the thermal performance of buildings, mechanical ventilation is usually stopped and heat loss by infiltration is included in the heat transmission of external walls. For the computer-simulated measurements in this research, the program NETS[2] [27] was used for combined simulation of heat, air, and tracer gas transfer. Simulated multi-zone infiltration measurements were also performed for reference.

2. System parameter estimation by double application of least-squares

2.1. Primary regression equation for diffusion system parameters

The framework of the spatial discretization model of a diffusion system can be written in the form of Equation (1), which is referred to as the nodal equation of a completely linked system. From this, the simultaneous ordinary differential Equation (2), also known as the state space equation, is constructed. Here, x_j, $m_{i,j}$, $c_{i,j}$, and $r_{i,j}$ are, respectively, diffusion variables such as the temperature of node j, the generalized capacitance of node i, the generalized conductance from node j toward node i, and the flux coefficient from the flux source j towards node i. Note that the flow direction is opposite the order of the subscripts i and j, in accordance with the linear algebra rule indicating element position in the matrix. In addition, n is the number of nodes with unknown values, no is the number of nodes with given values, and ng is the number of flux sources. Equation (2) is the entire equation for all nodes.

Generalized conductance $c_{i,j}$ such as infiltration or heat transfer by long wave radiation varies with temperature and time. Nevertheless the present methods are useful in cases where average results of the system identification term are sufficient. A linearizing approximation for long wave radiation is described in Appendix A.

$$\sum_{j=1}^{n} m_{i,j}\cdot\dot{x}_j = \sum_{j=1}^{n+no} c_{i,j}\cdot(x_j - x_i) + \sum_{j=1}^{ng} r_{i,j}\cdot g_j \tag{1}$$

[2] NETS is authorized by the Ministry of Land, Infrastructure and Transport, Japan, as a calculation method for building annual heating and cooling load, as of 22 October 2002.